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CONTRIBUTIONS FROM THE JEFFERSON PHYSICAL LABORATORY,
HARVARD UNIVERSITY.

ON THE COOPER HEWITT MERCURY INTERRUPTER.

By George W. Pierce.

With Three Plates.

ON THE COOPER HEWITT MERCURY INTERRUPTER.

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I. Introduction.

Mr. Peter Cooper Hewitt has devised a new form of interrupter designed to take the place of the spark-gap in the wireless transmission of signals and in the production of high potential discharges with the Tesla transformer. Mr. Hewitt's interrupter employs the discharge between mercury electrodes in an exhausted bulb instead of the usual spark in air between solid metallic terminals. Figure I is a diagram of the usual form of Cooper-Hewitt interrupter. At the bottom of an exhausted bulb 15 or 20 cm. in diameter are two deep depressions containing pools of mercury, between which the discharge is made to pass. Short pieces of platinum wire (1.5 mm. in diameter) fused into the glass serve to lead the current into the bulb. To prevent unequal heating of the sealed-in wires the two protuberances may be dipped into tumblers of mercury to which the connections are made.

Figure I.

In the preparation of the interrupters employed in these experiments the mercury for the bulbs was carefully purified by distillation and by washing through a nitric-acid filter; when the mercury is slightly contaminated the interrupter soon becomes inoperative. The bulbs were attached to a condenser and the source of current while being pumped, and their vacuum was tested from time to time during the exhaustion. In these tests care must be taken not to send the discharge through the interrupter when it contains too much air, as oxygen under the action of the discharge contaminates the mercury. When the vacuum was too low, the discharge through the bulb showed striations, and when the vacuum was too high, the discharge could not readily be started. The proper vacuum could be distinguished by the appearance of the bulb or by the

crackling sound it emitted; or, better, the proper vacuum could be determined by using the bulb as interrupter for a Tesla coil during the exhaustion.

Figure II is a diagram of the arrangement of the circuits as they are employed with the Tesla coil. C is a condenser charged from the secondary of a step-up transformer P S actuated by the 110-volt alternating light circuit. At intervals this condenser discharges through the interrupter I and through the primary P′ of the Tesla coil, as follows: When the potential of C becomes high enough to start the discharge, the resistance of the interrupter drops to a fraction of an ohm, and the electricity from the condenser surges back and forth through C P′ I. These

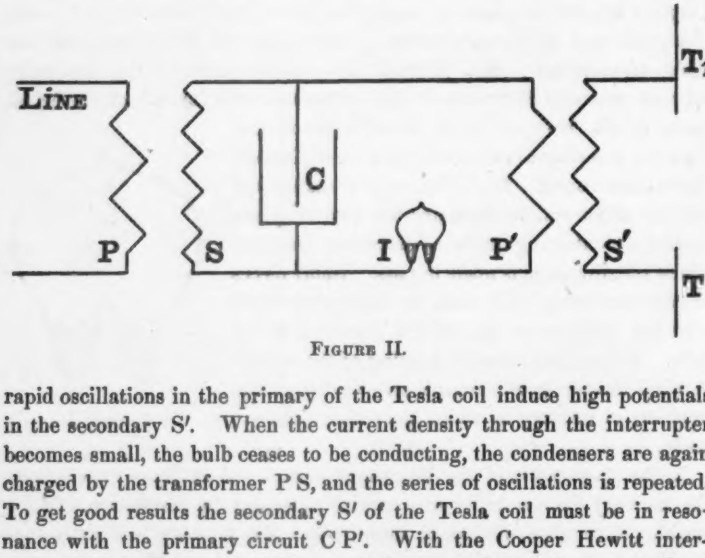

FIGURE II.

rapid oscillations in the primary of the Tesla coil induce high potentials in the secondary S′. When the current density through the interrupter becomes small, the bulb ceases to be conducting, the condensers are again charged by the transformer P S, and the series of oscillations is repeated. To get good results the secondary S′ of the Tesla coil must be in resonance with the primary circuit C P′. With the Cooper Hewitt interrupter at I the Tesla coil gives a much longer and a much more uniform discharge than when a zinc or an iridium spark-gap is employed as interrupter.

In one form of wireless telegraph circuit first suggested by Braun * and

* F. Braun, Phys. Zeit., 3, 143 (1901). Drahtlose Telegraphie durch Wasser und Luft, Leipzig, 1901. Simon and Reich, Phys. Zeit., 4, 365 (1903). M. Wien, Ann. der Phys., 3, 686 (1902).

See also the controversy between Braun and Slaby as to priority, in various recent numbers of Ann. der Physik.

now employed also by Marconi and by Slaby, the arrangement at the sending station is essentially the same as in the Tesla coil, with one of the terminals, T, put to earth and the other, T_1, attached to one or more vertical wires carried by masts. One object of this research is thus the attempt to discover in what way and to what extent the Hewitt interrupter is superior to the spark-gap in the wireless transmission of signals.

The study of the mercury interrupter is also of interest in its relation to the theories of electric conduction in gases and in its relation to the phenomena of electro-luminescence.

The present paper comprises:

II. Quantitative measurements of the induction between circuits with the two forms of interrupter in the sending circuit.

III. Resonance between such circuits.

IV. Photographs of the oscillations in the Hewitt interrupter with the aid of the revolving mirror.

V. Photographs showing the rapidity of recovery of the Hewitt interrupter.

VI. Calorimetric measurement of the ohmic resistance of the Hewitt interrupter.

VII. Determination of the proper vacuum for the Hewitt interrupter.

II. Quantitative Measurement of the Induction between Loops.

In order to obtain a direct comparison of the mercury interrupter with the spark in air between solid metallic terminals, I have measured the intensity of signals obtained in a receiving circuit with the two forms of interrupter respectively in the sending circuit. For a receiving instrument recourse was had to a form of oscillating current galvanometer devised by Fleming and employed in 1897 by Northrup, Pierce, and Reichmann* in an experiment on induction between distant circuits. Figure III is a diagram of this instrument. In the centre of the figure, between S and N, is a carefully insulated coil usually of about one hundred turns of fine wire. The coil has an internal diameter of about 1 cm., and is put in series with the receiving circuit by means of binding posts outside of the enclosing vulcanite box. For the purpose of varying the sensitiveness of the instrument, the coil may be removed and replaced by another of any desired number of turns. Within the coil is suspended a thin circular disc of silver foil about 6 mm. in diameter, to which a

* Electrical World, Dec. 18 and 25, 1897.

mirror is attached by a slender rod of glass. For sensitiveness the disc and mirror should be as light as possible. The suspension is hung by a fine quartz fibre so that the disc makes an angle of about 45° with the plane of the coil. By the oscillations in the receiving circuit, which pass also through the coil, oscillations are induced in the disc, which is thus repelled and tends to set itself at right angles to the coil. The vulcanite box, which encloses the suspension, is provided with a glass face through which the deflections may be read by a telescope and scale. The period of the instrument is five seconds, and the suspension is so light that its deflections are practically dead-beat, rendering unnecessary the damping magnet S N that was employed in the earlier experiments.

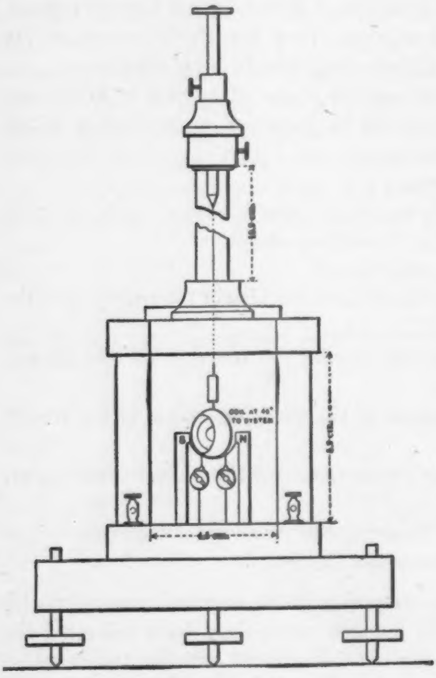

FIGURE III.

When used in ordinary wireless telegraph circuits this instrument shows great sensitiveness. In making the present comparisons, the data are obtained not from ordinary wireless telegraph circuits of the "open" type, but from circuits consisting of closed loops. These circuits are of the same form as those previously employed by Northrup, Reichmann, and the author, and are represented in Figure IV. The sending circuit A consists of a glass condenser a in series with the spark-gap or interrupter b and a rectangular loop of wire four meters by three meters. About the spark-gap or interrupter are connected the terminals of the secondary of a step-up transformer, actuated by the alternating electric light circuit. The spark-gap is made of small pieces of iridium set in heavy brass balls. By

throwing a switch the Hewitt interrupter may be put in the place of the iridium spark-gap.

The receiving circuit B is at a distance of twenty meters from the transmitting circuit. The receiving circuit consists of a variable air-condenser in series with the receiving instrument and a closed rectangular loop (2 m. × 1 m.) of wire in a plane parallel to the sending circuit. When the receiving circuit is brought to approximate resonance with the sending circuit, large deflections of the instrument are obtained. In taking readings the discharge was kept up during the period of swing of the instrument, and throws were read.

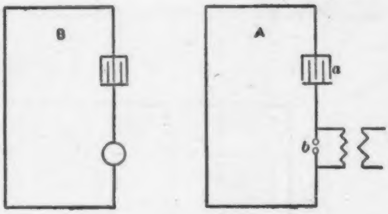

FIGURE IV.

The following sets of readings (Table I) are given to show the uniformity and effectiveness of the mercury interrupter in comparison with the iridium spark-gap. The columns of readings were taken in the order given in the table. A rheostat in the primary circuit of the transformer was adjusted so that the mercury interrupter functioned vigorously; the set of readings in the first column were taken, then without changing the receiving circuit of the rheostat, the iridium spark was put in the place of the mercury interrupter, and was adjusted in length to give its best deflection. With this adjustment readings in the second column were taken. The third column shows another set of readings with the mercury interrupter. The fourth column is with the spark-gap. The readings are in centimeters with a scale distance of 60 cm.

Whence it is seen that the deflections with the mercury interrupter are about four times as large as the deflections that could be obtained under similar conditions with the iridium spark-gap. Other comparisons with various capacities and inductances in the circuits gave likewise substantially larger deflections with the mercury interrupter than with the spark-gap. With this interrupter the spark at the secondary of a Tesla coil was also four or five times as long as that obtainable with the iridium spark-gap. The increased spark length with the Tesla coil did not, however, indicate an increase of integral effect in the secondary, as the sparks may have been fewer in number. Hence, the experiment with induction between loops was made. The result shows that the

total energy communicated between the circuits was about four times as great with the mercury interrupter as with the spark-gap. The results here given pertain, of course, only to the particular form of circuits and the particular interrupter employed. I have made some experiments with forms of open circuit of the type used in wireless telegraphy, but the results are not yet ready for presentation.

TABLE I.

C. H.	Spark.	C. H.	Spark.
25.9	6.4	26.4	7.7
25.8	6.5	26.3	6.8
26.5	6.4	26.0	6.4
25.8	6.7	26.6	6.4
26.3	6.7	25.9	6.5
27.1	6.7	25.8	6.4
27.0	6.8	27.7	6.3
25.2	6.4	26.1	6.8
26.2	6.7	27.5	6.5
26.2	6.8	26.9	6.3
26.3	6.62	26.5	6.62 mean.

III. Resonance.

On account of the regularity of the mercury interrupter, it can be employed advantageously in the study of resonance between circuits of high frequency. For example, the *closed loops* used in this experiment can be quite accurately tuned with the aid of this interrupter and the receiving instruments described above. With a fixed sending circuit the accompanying curve (Figure V) was obtained by a single set of readings when the air condenser in the receiving circuit was varied from six plates up to twenty-one plates. The capacities are represented as abscissas, while the deflections in centimeters are the ordinates. The capacity for each plate of the air condenser is 248 cm. The capacity

at resonance can easily be located within one or two per cent. I have not been able to get quite such smooth resonance curves when the spark-gap is employed as interrupter in the sending circuit. Experiments are now in progress with commercial wireless telegraph circuits, instead of the closed loops.

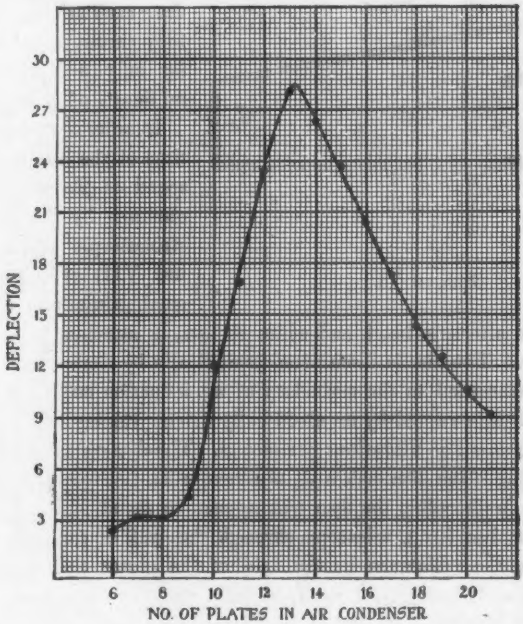

FIGURE V.

IV. PHOTOGRAPHS WITH THE REVOLVING MIRROR.

In the search for an explanation of the greater uniformity and effectiveness of the mercury interrupter in producing inductive action between circuits, I have taken a series of photographs of condenser discharges through the interrupter. For this purpose the familiar revolving-mirror apparatus was employed (Figure VI). The concave mirror M has a focal length of 1.52 meters, and is driven by a battery motor at a speed of twenty to seventy revolutions per second. The interrupter, mirror, and plate are in a light-tight box, of which the end carrying the photographic plate projects into a dark room. Neither side

of the sensitive plate is covered, so that the observer, who charges the condenser from a step-up transformer by operating a switch in the dark room, can see a flash upon the plate when the plate is struck. In fact, he can see quite plainly each of the oscillations, though they persist in some cases for only a fraction of a millionth of a second.

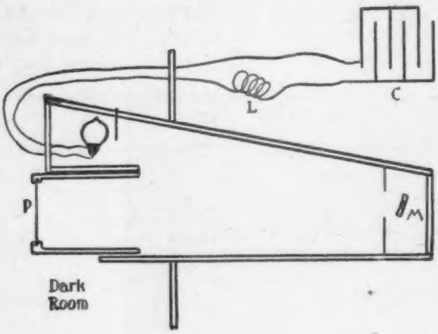

FIGURE VI.

In order to measure the time of the discharge, the speed of the mirror was obtained by the aid of a stroboscopic device (Figure VII) as follows: A small aluminum disc D, marked off in alternate black and white sectors, is attached to the axis of the mirror. The disc is illuminated periodically by flashes in a Geissler tube G, connected to the secondary of an induction coil C, of which the primary is interrupted by an electrically driven tuning-fork T. The tuning-fork makes 256 vibrations per second. The disc contains 12 black sectors; so that if the disc makes $\frac{1}{12}$ of a revolution between two consecutive flashes in the tube, the disc will appear to stand still. Thus by observing the disc (by a telescope through the wall of the dark room) and adjusting the resistance in the field of the motor that drives the mirror, the disc is brought to an apparently stationary condition. The mirror is then making $\frac{1}{12}$ of $256 = 21.33$ revolutions per second. Other apparently stationary conditions of the disc correspond to 42.66 and 64 revolutions per second. It is not difficult to set on these speeds with an accuracy of one or two tenths of one per cent.

The mercury interrupters of which the accompanying photographs were taken were so constructed that the mercury surfaces were brought near to each other (about 1 mm.), so that the image of both electrodes fell near together on the plate.

The revolving-mirror photographs of the mercury interrupter and of the ordinary spark in air between cadmium terminals are shown in Plate I.

When the mercury interrupter in action is viewed directly by the eye at rest, without the intermediation of the revolving mirror, it shows

an intense luminescence throughout the bulb, while brilliant flashes are thrown up from both electrodes all around the line of contact of the mercury with the glass. It looks as if a great many of these little fountains of fire occur simultaneously. The revolving mirror shows, however, that their occurrence is usually successive, — each little flash going through its series of oscillations and dying out before another flash appears. It is thus not difficult to make the exposure so short that only one fountain with its oscillations appears on the plate. By diaphragming the bulb and adjusting the position of the sensitive plate the pictures of Plate I, Figures 1, 3, and 4, were made to take in only the illumination of the nearer regions of the electrodes. The mirror was turning in the direction from the bottom of the cut towards the top, and the two vertical lines of impressions in Figures 1, 3, and 4 are respectively the oscillations at the two electrodes. The picture of Figure 3, which is clearer, shows that a bright point of light appeared first on the electrode to the left, and that this spot persisted for a time sufficient for the mirror to turn through a distance indicated by the length of the bright spot on the plate. During this time the point of light widened a little and then died out. Shortly after the extinction of the illumination at the left-hand electrode, a bright spot appeared on the electrode at the right. After this disappeared a second illumination occurred on the left, and so on for a series of oscillations whose number depends on the self-inductance, capacity, and resistance of the circuit. Figure 1 (Plate I) shows four oscillations at a single electrode. Figures 2 and 5 of Plate I are the

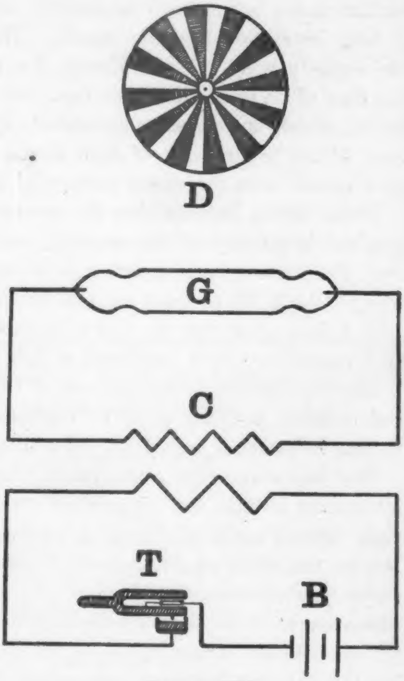

FIGURE VII.

familiar photographs taken in the same way with the discharge in air between cadmium terminals. The two terminals become successively luminous in an oscillatory fashion.

In Figures 1, 3, and 4 of Plate I light bright enough to affect the photographic plate is obtained only from one of the electrodes, the cathode. The exposure is too short to show what happens at the anode. By the use of a larger capacity and a larger inductance the period of oscillation can be increased so that the exposure is long enough to get a faint impression from the anode. This was done in a case where the capacity was .117 microfarads, the inductance .0071 henries, and the time of an oscillation, therefore, .000178 second. The picture obtained, which is not here reproduced, showed that, during the existance of the bright point of light at the cathode, there is also a weak glow spread over the entire surface of the anode.

These results indicate that the current whose action is here photographed is exactly of the same character as the mercury arc, except that the current is reversed several times during the condenser discharge; for in the mercury arc with direct current the anode is covered with a faint glow over its entire surface, while the cathode region is dark except for a very small spot of light of extreme brilliancy.

The fact that the several pictures of Plate I show different frequencies and different damping is of no significance, as they were made with various inductances, capacities, and resistances in the circuit of discharge.

One important fact about the pictures obtained with the mercury interrupter is that the impressions are so sharp (in the negative) that their distance apart (cf. Figure 1, or the distance from the first to the last on the left-hand electrode of Figure 3) can be measured with great accuracy, which makes this form of interrupter useful in the photographic measurement of the time of a condenser discharge. For example, taking the stroboscopic determination of the speed of the mirror and measuring the distances between impressions on various photographic plates, the values given in Table II were obtained for the time in seconds of a double oscillation.

The measurements in the last column were made with a cadmium spark-gap instead of the mercury interrupter, and show larger variations than the columns obtained with the interrupter.

Measurements similar to those of Table II have been utilized in the determination of the capacity of the condensers and the inductance of the leads,— quantities that are needed in the discussions of section VI of this paper. The determination of these quantities was made as follows.

TABLE II.

23 Plates in Glass Condenser.

Inductance.	Coil I. and Leads.	Leads.	Coil II. and Leads.
Time in sec.	2.30×10^{-5}	$.588 \times 10^{-5}$	7.90×10^{-5}
	2.30	.585	8.03
	2.28	.584	8.10
	2.29	.585	8.12
	2.30	.584	7.90
	2.30		8.12
	2.29		8.03
Mean	2.295	.585	8.03
Mean error	.3%	.2%	.9%

Coil I and coil II are accurately wound, and their inductances, L_1 and L_2 have been calculated from their geometrical dimensions.

$$L_1 = 1.06 \times 10^5 \text{ magnetic units,}$$
$$L_2 = 14.1 \times 10^5 \quad \text{"} \quad \text{"} \; .$$

Let $L =$ the unknown inductance of the leads, then by Thomson's formula, we have from Table II,

$$2\pi\sqrt{(L_1 + L)C} = 2.295 \times 10^{-5} \tag{1}$$
$$2\pi\sqrt{LC} = .585 \times 10^{-5} \tag{2}$$
$$2\pi\sqrt{(L_2 + L)C} = 8.03 \times 10^{-5} \tag{3}$$

Eliminating C from (1) and (2), we have $L = .073 \times 10^{-5}$, which, substituted in (2), gives

$$C = .1175 \times 10^{-15} \text{ magnetic units,}$$
$$= 1.05 \times 10^5 \text{ cm.}$$

Likewise, from equation (3)

$$C = 1.04 \times 10^5 \text{ cm.}$$

When we remember that the percentage error of the time is doubled in the calculation of capacity, it is seen that these two computed values of C agree with an error not greater than the error of observation, or the errors possibly made in the computations of L_1 and L_2.

In this way the inductance of the leads and the capacities of the condensers were determined in a number of cases (Table III) to be used in the discussion of the results obtained in section VI for the resistance of the interrupter.

TABLE III.

n = the number of plates in condenser,
T = period in millionths of a second for the discharge through the leads alone.
T' = period through leads and .000106 henries in series.

n.	T.	T'.	Inductance of Leads in Henries (calc.)	Capacity in Microfarads (calc.)
3	2.39	7.76	.0000111	.0130
7	3.78	12.1	.0000116	.0318
19	6.14	18.6	.0000130	.0730
24	7.48	23.5	.0000120	.1170

In putting in additional condensers up to nineteen plates the inductance of the leads had to be increased, hence the progression in the first three values of column four. To get twenty-four plates, plates were introduced back nearer to the interrupter by leads whose direction was such as to diminish the inductance, giving the smaller value of inductance in the last line. The capacities are correct within about 1%. The inductances having been determined as a difference, may contain an error as great as 2%.

V. Photographs Showing Rapidity of Recovery of the Mercury Interrupter.

The revolving-mirror photographs of the mercury interrupter show that when the condenser in series with the interrupter is charged to a sufficiently high potential the matter in the globe in some way becomes conducting, and that this conductivity continues during a series of oscillations. In this respect no difference is apparent between the action of the mercury interrupter and the ordinary discharge of the condenser between metallic terminals in air. It thus occurs to one that the advan-

tage of the mercury interrupter may lie in the rapidity of recovery of the nonconducting character of such an interrupter after the discharge has passed, so that the condenser which is connected to the transformer may again be charged to a high potential and may thus again quickly accomplish a strong series of oscillations.

To test this point, a number of photographs (Plates II and III) of the mercury interrupter and the spark in air were taken to ascertain how many times distinct series of oscillations occur during a single cycle of the charging transformer. The pictures were taken upon films or sheets of bromide paper attached to a rapidly rotating disc. The image of the interrupter was focussed upon the sensitive paper or film by a lens of short focal length. To avoid overlapping of the pictures on the film when the disc made more than one revolution during the exposure, the lens was mounted in a pendulum, and the exposure was made by swinging the lens behind a diaphragm in front of the revolving film. In this way the image, instead of moving in a circle, was made to trace out a spiral on the film. With such an apparatus the motion was too slow to resolve the discharge into its separate oscillations. On the other hand, each *series* of oscillations constituting a *complete discharge* made an impression upon the plate. The speed of the motor could be varied so as to take from one to four cycles of the transformer per revolution. The period of the transformer, $\frac{1}{60}$ second, served as a measure of the speed of the motor.

In order to obtain an understanding of these pictures it must be remembered that the secondary of the transformer was attached permanently to the condensers; the primary of the transformer was closed, and the condensers were allowed to charge directly and to discharge through the interrupter. During this action of the interrupter, the pendulum containing the lens was allowed to drop, thus making the exposure.

Simon and Reich * have already shown by a photographic method that several discharges may occur during a single half-cycle of the transformer. Evidently, the number of such complete discharges, each with its series of oscillations, will depend on the capacity of the condenser, the inductance of the secondary of the transformer, and the potential at the terminals of the secondary of the transformer. For a given secondary, as we increase the charging potential by increasing the current in the primary of the transformer, the number of charges and discharges will increase. Their number will also increase with decreasing condenser capacity.

* Phys. Zeit., 4, 361 (1903).

With a large capacity the number of discharges occurring during the half-cycle is small. In Figure 6, Plate II ($C = .117$ microfarads, $V = 15{,}000$ volts), only one, or sometimes two, discharges occur during the half-cycle of the transformer. In this picture the whole of the mercury-vapor bulb together with the bright surfaces of the electrodes

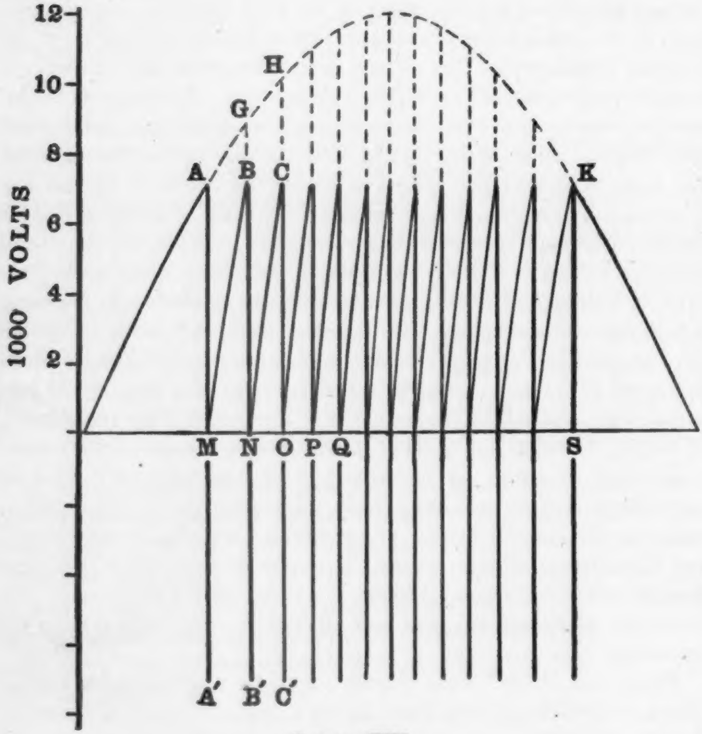

FIGURE VIII.

are shown, while the legs of the interrupter, of course, make no impression on the film. The images are arranged in the form of a spiral on the film. Both electrodes are bright, for several oscillations occur during each discharge.

By keeping the voltage of the transformer the same and reducing the capacity about thirty-fold, Figure 7, Plate II was obtained. In taking this photograph, to prevent confusion, the greater part of the bulb was

covered by a paper screen, leaving only the electrodes and the lower part of the bulb to be photographed. In this case ($C = .0043$ microfarads, $V = 15{,}000$ volts) about sixty complete discharges occur during the half-cycle of the transformer, which is $\frac{1}{120}$ second.

By lowering further the capacity of the condensers and raising the potential of the transformer, the number of discharges may be greatly increased and the period of rest at the reversal of the cycle can be made small, so that the attempt of Simon and Reich to make the mercury interrupter operate on a direct current can be approximately realized with the transformer as source of current.

In order to obtain an understanding of the succession of charges and discharges through the interrupter let us examine the photograph of Figure 8, Plate III, which is a *negative.* In this case the capacity was .0130 microfarads, the maximum potential of the transformer cycle 12,000 volts. The numbers of complete charges and discharges during successive half-cycles of the transformer are seen to be 12, 11, 12, 13, 13, 9, 11, 12, 11, 12, 12, 16, 13, 13, 12, 11, 13, 11, 14, 12, 12. By a separate experiment it has been shown that with the particular interrupter the condensers *begin to discharge* when their potential is 7070 volts, whatever the capacity of the condensers.

If the condensers always discharge at 7070 volts throughout each series, and if we neglect the reactance of the discharges on the potential of the transformer, the diagram of Figure VIII would represent approximately the manner in which the discharges occur. The sine-curve of Figure VIII represents the potential of the open-circuited secondary of the transformer with condenser in series. This curve is plotted with voltage as ordinates and epoch as abscissas. When about 7070 volts is reached, for this particular interrupter, the condenser discharges with a series of oscillations up and down the line A M A′. The condenser again charges along the practically straight line M B, and discharges again along the line B N B′, and so on. The rapidity with which the condenser charges, after any given series of oscillations, is approximately proportional to the potential of the transformer during the charge, so that the areas M A G N, N G H O, . . . should be equal; thus a division of the area M A G H K S into equal n smaller areas M A G N, N G H O, . . . ought to give the distribution of the discharges M, N, O, . . . S.

The construction of Figure VIII is slightly erroneous, for the discharge is never complete, but with the present interrupter always leaves the condenser charged to about 1600 volts. This residual voltage chances sometimes to be positive and sometimes negative, which is a possible

explanation of the irregularities apparent in the distribution of the images in the actual photographs. The similarity of their distribution at the beginning of a series and their distribution at the end of a series shows that *the accumulated effect of a number of discharges does not render the bulb conducting so as to weaken succeeding discharges.*

By the use of a small Leyden jar as capacity and a charging potential of 15,000 volts, I have been able to obtain over 200 complete discharges, each with its series of oscillations, during one-half cycle ($\frac{1}{120}$ second) of the charging transformer. These complete discharges, comprising each many oscillations, were separated by an interval of time of about $\frac{1}{100,000}$ of a second, yet every discharge was sharp, definite, and regular, and showed that even after a long operation of the interrupter at this frequency of charging the bulb did not become filled with conducting vapor or conducting ions so as to lower materially the potential of succeeding discharges. This seems to me to be a very important part of the whole advantage that the Cooper-Hewitt mercury interrupter has over the spark in air.

Figure 9, Plate III, is a typical example of the behavior of a spark in air when produced by a high potential. This is a picture of a spark between zinc terminals taken with a rotating film. Each spot is the image of a complete discharge with its series of oscillations. It is seen that these discharges at the beginning of a cycle are strong, but throughout the cycle become spasmodically strong and weak, showing that the spark-gap often retains its conducting character long enough to prevent the proper subsequent charging of the condenser. This discussion may apply only to the case in which the condenser is charged by some persistant source of current like the transformer. I have not ascertained whether a similar result is to be found when the condensers are charged by an induction coil or a static electric machine.

VI. The Resistance of the Mercury Interrupter.

In measuring the mean resistance of the mercury interrupter, I have made use of a calorimetric method similar to that employed by Battelli and Magri * in their determination of the resistance of a spark-gap in a series of measurements on condenser discharges. A calorimeter containing the mercury interrupter was put in series with a calorimeter containing a known resistance. The discharge from the condenser while connected to the transformer was allowed to pass for a suitable

* Phys. Zeit, 3, 539 (1901-1902).

time through the known resistance and the interrupter in series. Since the heating of both resistances was produced by the same current, the

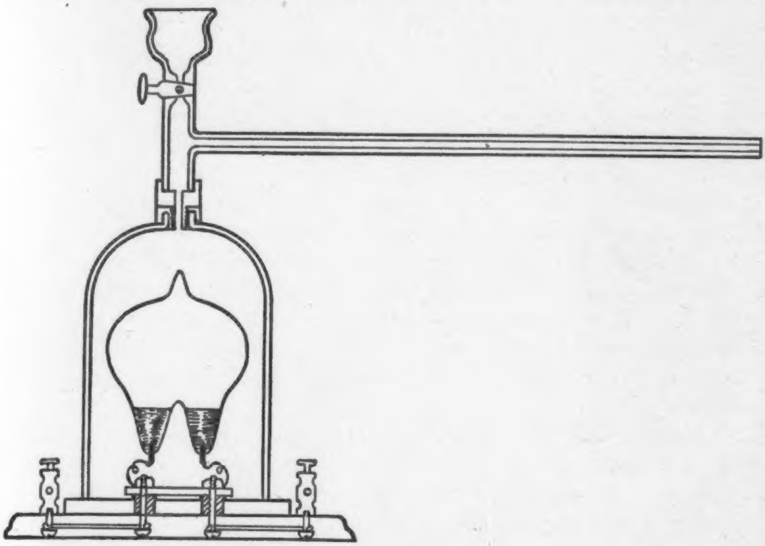

FIGURE IX. CALORIMETER A.

heat developed in the two calorimeters was proportional to their respective resistances. The calorimeters are shown in Figures IX and X. Figure IX is the calorimeter about the mercury interrupter (calori-

FIGURE X. CALORIMETER B.

meter " A "). In its construction a glass bell-jar was put down over the interrupter and cemented with fish-glue and plaster of Paris to a thick glass plate provided with two holes, through which the leads to the

interrupter were admitted. Into the neck of the bell-jar, by means of a screw-connector, was fitted a funnel-tube closed above by a stop-cock and communicating with a horizontal glass capillary to be used as an index. The bell-jar, funnel-tube, and a part of the capillary were filled with a light transformer oil. The expansion of the oil, read on a scale attached to the capillary, served as a measure of the heat developed in the jar. Within the oil, around the interrupter, black paper was loosely wrapped to prevent radiation.

For comparison with calorimeter A, two calorimeters "B" and "C" of different resistances were constructed of the form shown in Figure X. The resistance consisted of a straight manganine wire connected by springs of copper to thick pieces of platinum sealed into the ends of a glass tube 8 cm. in diameter. This tube was also filled with oil and provided with a capillary index similar to that of calorimeter A. The manganine wire was supported axially within the tube by circular discs of glass. About these discs of glass, within the oil, half-way between the wire and the walls of the tube, a cylinder of black paper was wound to prevent radiation. The resistance of the manganine wires of calorimeters B and C was measured on a Wheatstone bridge. Computed by Rayleigh's formula, the correction for surface travel when these wires should be used with the oscillatory current, was found to be negligibly small on account of the high specific resistance of the material of the wires. The calorimeters B and C had the following constants:

Calorimeter.	Length of Wire in cm.	Diameter of Wire in cm.	Resistance in Ohms.
B	66	.078	1.025
C	48	.108	.258

To determine what amount of heat corresponded to 1 cm. of expansion of the oil, the three calorimeters were calibrated by a *direct dynamo current* through the bulb of the mercury interrupter and the two manganine wires in series. The current was started, as in the Aaron's lamp, by tipping the bulb so that the mercury of the two electrodes came momentarily together. The energy expended in the three calorimeters by the calibrating current could now be calculated from the current, the voltage about the interrupter, the resistances of the two manganine wires, and the time.

Having in this way obtained the amount of heat required to give one centimeter of expansion on the scale of each of the calorimeters, the resistance of the mercury interrupter for the oscillatory discharge was measured for various inductances and capacities of the discharge circuit. The resistance of the interrupter was found to vary with the capacity and inductance. When this resistance was large, the calorimeter B was used in the comparison; when it was small, C was used. To make sure that the two comparison calorimeters were consistent, the resistance of the interrupter was occasionally measured by both B and C and found to give concordant results.

In making the final measurements with the oscillatory current the mercury interrupter in the calorimeter A was put in the discharge circuit in series with the known resistance of one of the comparison calorimeters. The secondary of the transformer was connected to the condenser, a switch in the primary of the transformer was closed, and the condenser was allowed to charge and discharge for a time varying from twenty to sixty seconds. The expansion of the oil of the two calorimeters was read, and then observations on the cooling of the calorimeters were taken for four minutes, so that the correction for cooling could be estimated.

At the end of the series of resistance measurements, the inductances and capacities of the various circuits were measured with an accuracy of about one per cent by the photographic measurement of the time of the condenser discharge. A sketch of the method of the computations for this purpose is given in section IV, p. 399 of this paper. The advantage of this method of determining the constants of the circuit is that it gives these constants for the required frequency.

The following tables (Tables IV, V, and VI) give a series of results for the resistance of the interrupter for various capacities and inductances.

From these tables it is seen that the resistance of the mercury interrupter decreases with increasing capacity of the condensers, and decreases with decreasing inductance of the discharge circuit.

These facts might perhaps be anticipated from the relation between the voltage and the current in the mercury arc with direct current, and the relation between the capacity, inductance, and current in the condenser discharge.

For direct currents greater than 3 amperes the voltage about the mercury arc is practically constant, and equal to 16 volts for the particular bulb here employed; therefore,

$$iR = \text{constant} = 16. \qquad (1)$$

TABLE IV.

INDUCTANCE = .0000110 HENRY. DISCHARGE POTENTIAL, 7070 VOLTS.

Capacity in Microfarads	.0130	.0313	.0730	.117
Period, Millionths of Sec.	2.39	3.78	6.14	7.48
Resistance of Mercury Interrupter in Ohms .	.29	.23	.16	.12
	.29	.21	.14	.11
	.23	.22	.13	.14
	.31	.21	.13	.13
	.27	.23	.14	.13
	.30	.22	.13	.13
	.29	.21	.13	.13
Average	.284	.219	.137	.127
$R\sqrt{C} \times 10$	.32	.38	.37	.43

TABLE V.

INDUCTANCE = .000117 HENRY. DISCHARGE POTENTIAL, 7070 VOLTS.

Capacity in Microfarads	.0130	.0313	.0730	.117
Period, Millionths of Sec.	7.76	12.1	18.6	23.5
Resistance of Mercury Interrupter in Ohms .	.69	.45	.25	.20
	.66	.48	.23	.20
	.68	.45	.23	.20
	.63	.48	.24	.18
	.64	.43	.23	.22
	.69	.43	.24	.20
	.68	.40	.23	.20
Average	.667	.444	.236	.20
$R\sqrt{C} \times 10$	.76	.78	.64	.68

TABLE VI.

INDUCTANCE = .00142 HENRY. DISCHARGE POTENTIAL, 7070 VOLTS.

Capacity in Microfarads			.0730	
Period, Millionths of Sec.			64.7	
Resistance of Mercury Interrupter in Ohms .			.60	
			.60	
			.59	
			.63	
			.60	
			.59	
			.58	
Average			.598	
$R\sqrt{C} \times 10$			1.62	

Now the current for the simplest case of a condenser discharge is given by the equation

$$i = \frac{2EC}{\sqrt{4LC - R^2C^2}} e^{\frac{-Rt}{2L}} \sin \omega t. \tag{2}$$

If the resistance is negligible in comparison with $2\sqrt{\frac{L}{C}}$ the square root of the mean square value of i becomes (neglecting damping)

$$I = \frac{1}{\sqrt{2}} \frac{\sqrt{C}}{\sqrt{L}} E. \tag{3}$$

If the relations (1) and (3) were exact, we should have for a given inductance

$$\sqrt{C}\,R = \text{constant}, \tag{4}$$

and for different values of the inductance

$$\frac{\sqrt{C}}{\sqrt{L}} \times R = \text{constant}. \tag{5}$$

We should not expect the relations (4) and (5) to be exact, because, first, equation (2) is obtained on the assumption that the resistance in the discharge circuit is independent of the current, which is a contradiction of (1), and, second, equation (1) is not true for small values of the current. Especially is (5) inaccurate because we have neglected the effect of the inductance on the damping.

An examination of the experimental data of Table IV, V, and VI shows that the inductance relation (5) is not verified. On the other hand, with a constant inductance $\sqrt{C} \times R$, for an eight-fold variation of C, is near enough to a constant to be of use, perhaps, in certain cases where only a rough approximation is required.*

For comparison with the resistance of the mercury interrupter, as obtained in these experiments, the following tables VII and VIII for the resistance of the ordinary spark in air are taken from the researches respectively of Lindemann † and Battelli and Magri.‡ These experi-

* This result is not to be confused with the apparently more exact relation found by Lindemann for the dependence of spark-energy on capacity.

† Lindemann, Ann. der Phys., **12**, 1012 (1903).

‡ Battelli and Magri, Phys. Zeit., **3**, 539 (1901–1902), and **4**, 181 (1903–4).

menters, by a bolometric method and a calorimetric method respectively, have measured the resistance of the spark in air between solid metallic terminals. For a proper comparison we should take the resistance for those spark-lengths that require the same potential to start the discharge as is required by the mercury interrupter (7070 volts).

TABLE VII.

RESISTANCE OF SPARK. R. LINDEMANN.

Inductance Henries.	Capacity Microfarads.	Spark Length mm.	Disch. Pot. Volts.	Resistance of Spark in Ohms.
.00000560	.00496	.67	3300	2.72
.00000560	.00496	1.16	5100	2.59
.00000560	.00496	1.58	6500	2.44
.00000560	.00496	2.24	8550	1.78
.00000560	.00496	.40	2224	2.18
.00000560	.00982	.40	2224	1.42
.00000560	.01593	.40	2224	1.055
.00000560	.02131	.40	2224	1.255

TABLE VIII.

RESISTANCE OF SPARK. BATTELLI AND MAGRI.

Inductance Henries.	Capacity Microfarads.	Spark Length mm.	Disch. Pot. Volts.	Resistance of Spark in Ohms.
.0000741	.0158	2	8301	.323
.0000295	.0158	2	8085	.341
	.00797	2	8220	.551
	.00397	2	8190	.723
.0000175	.00397	2	8103	.564
.00000367	.00397	2	7635	.290

Among the results given by Lindemann only the fourth value of Table VII. is appropriate for these comparisons. Lindemann's value is

1.78 ohms. A single observation that I made with the mercury interrupter and with capacity and inductance about equal to those of Lindemann in this case gave .60 ohms. Extrapolations from the other values obtained by Lindemann indicate that for the same discharge potential, and corresponding capacities and inductances, his method gives for the resistance of the spark in air, values perhaps three or four times as large as the resistance of the mercury interrupter.

On the other hand, it is seen from Table VIII that the values obtained by Battelli and Magri for the resistance of a 2 mm. spark in air between solid metallic terminals * are of about the same magnitude as the values I obtained for the resistance of the particular mercury interrupter. The discharge potentials in the two cases were approximately the same.

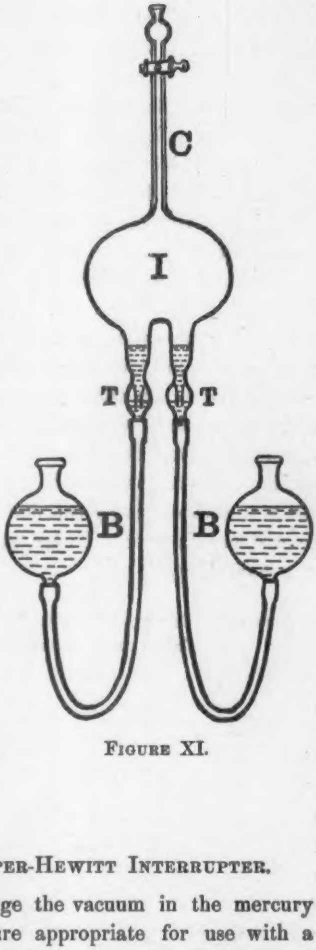

Figure XI.

Lindemann's observations were made with a single discharge, while those of Battelli and Magri and those of the author were made with a great number of discharges following each other in rapid succession. This latter arrangement would be the condition under which the resistance would be least. I found, however, that a considerable change in the rapidity of charging made no appreciable change in the resistance of the mercury interrupter.

VII. The Vacuum of the Cooper-Hewitt Interrupter.

In order to be able rapidly to change the vacuum in the mercury interrupter and to measure the pressure appropriate for use with a transformer capable of giving about 15,000 volts, the apparatus of

* Battelli and Magri found the same resistance whether they employed platinum-iridium or cadmium terminals.

Figure XI was devised. The protuberances of the bulb I, instead of being provided with platinum terminals, were left open, and to them rubber tubes were connected. The other ends of the rubber tubes were connected to reservoirs containing mercury. To the top of the bulb I was fused a capillary tube of uniform bore closed above by a stop-cock. The vessels B B were stationary, and the bulb I could be lowered with stop-cock open so as to fill with mercury. The bulb I was then raised with stop-cock closed to a height greater than the barometric column, and was thus exhausted. Traps T T in the protuberances of I prevented air bubbles, which escaped from the rubber tube, from entering the bulb. The bulb, which could thus be exhausted to any desired degree, was connected through the mercury columns in series with the primary of a Tesla coil, of which the discharge at the secondary served as a test of the correctness of the vacuum. The vacuum could be measured by lowering I with stop-cock closed, and bringing the residual gas under atmospheric pressure into the capillary C. It was found that with the particular voltage at my disposal (15,000 volts), the Tesla coil gave its best action when the pressure in the cold bulb, before the discharge, was about .02 mm. When the pressure was two or three times this amount the bulb gave a brilliant arc, while the spark at the terminals of the secondary was feeble. For pressures lower than .02 mm. (cold) the bulb showed pale green luminescence resembling somewhat the glow in a Roentgen tube. Under these circumstances the condensers seemed not to discharge.

Jefferson Physical Laboratory, Harvard University,
Cambridge, Mass., Dec. 20, 1903.

Fig. 1.

Fig. 2

Fig. 3.

Fig. 4.

Fig. 5.

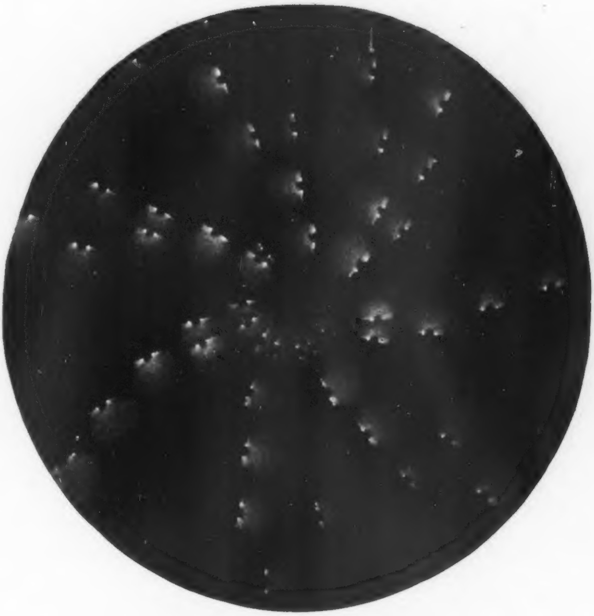

Fig 6.

Fig. 7.

Fig. 8.

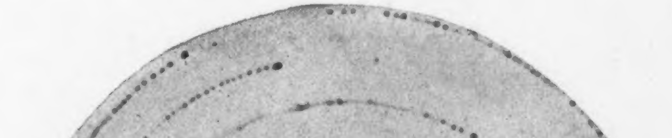

Fig. 9.